ESTIMATING PRECIPITATION AT SAN FRANCISCO FROM CONCURRENT METEOROLOGICAL VARIABLES[1]

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ABSTRACT

Variables obtained from synoptic sea level and upper air charts are investigated to determine their significance in the estimation of concurrent rainfall. Eight variables consisting of sea level pressures and pressure gradients, pressure heights and height differences, and the temperature-dew point differences at two upper levels are combined into a graphical procedure to estimate the probability of occurrence of rainfall. With the probability of occurrence rising to above 50 percent, supplementary charts are used to estimate the amount of rainfall to be expected.

INTRODUCTION

In making a forecast the usual procedure is to predict the movement and expected change in intensity of pressure systems, with their associated fronts, and the expected positions and intensities of upper air troughs and ridges [1]. Although these expected changes are often treated in a subjective manner, the final stage of such a forecasting procedure may well lead to the actual construction of prognostic charts of the synoptic conditions expected at some period in the future. However, experience has indicated that even if accurate prognostic pressure and upper level contour charts were available, forecasters would still not be able to give a complete picture of the accompanying weather conditions. Thus, a study leading to an increase in the knowledge of the current weather to be expected from a given synoptic situation is of interest to the forecaster. In a study of this type, the synoptic charts take the place of the prognostic charts which are expected to be used eventually in the forecasting system. Such a study will furnish information as to the significance of commonly observed variables and indicate the accuracy which may be attained through their use.

Of additional interest is the possibility that a study of this nature may lend itself to the evaluation of attempts to modify the weather. During the past few years the problem of evaluating the effect of cloud seeding on the production of rainfall has become of considerable importance. This problem has no easy solution. The difficulty lies largely in the fact that the areal distribution of rainfall for the individual storm has great variability, and further that the final solution lies in the realm of statistics where a definite yes or no answer is not forthcoming. It is fairly obvious that if a method could be devised which would establish a perfect correlation between meteorological variables and the associated rainfall at a given point, the problem of evaluating rainmaking at that particular point would be solved—on the condition that the seeding itself had no influence on the meteorological variables (a condition perhaps not fulfilled for all variables used in this study). The nature of the weather problem precludes the attainment of perfect correlation and the eventual value of the derived method would depend upon the degree of correlation which is obtained.

GENERAL ASPECTS OF THE RAIN PROCESS

Meteorologists are not in full accord as to the prerequisite conditions for the occurrence of rain. Although knowledge of the precipitation mechanism is increasing, a great deal is yet to be learned about the exact physical conditions leading to rainfall. In the consideration of factors favorable for the production of rainfall, the most common agreement appears to be that upward motion of the air and the presence of sufficient moisture are of predominant importance [2]. Of less general agreement is the extent to which the occurrence of rain depends upon the temperature distribution within the cloud system, the number and nature of nucleating particles, the drop-size distribution of the cloud, and various other factors.

In estimating the occurrence and amount of precipitation the meteorologist is faced with the fact that, with the possible exception of the moisture, the physical factors entering into the production of rain are not measured directly. The existence of large-scale vertical motions in the atmosphere must be inferred from the analysis of the major air currents [3]. No information is available as to the number of particles in a given airmass which may serve as nucleating or sublimating agents, nor is there any synoptic information concerning the distribution of drop-

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size within a particular storm cloud. Accordingly, an estimate of the effects which the existing combination of physical factors has on the production of rainfall must be obtained indirectly. In practice, it is the usual procedure in making a forecast to go directly from the prognosticated synoptic features to the expected weather, thus bypassing the actual consideration of the quantitative effects of the physical factors. However, a thorough understanding of the physical process may suggest significant meteorological variables for use in a forecasting system. A considerable number of variables suggested by theory and synoptic experience were investigated. In general, it was found that variables involving pressures and pressure heights were more effective in determining rainfall at the station studied than were those involving temperature and stability. Only those variables showing the greatest effectiveness were used in the estimating procedure which was developed.

PURPOSE OF STUDY

This study was carried out in order to investigate the effectiveness of commonly observed synoptic factors as indicators of concurrent rainfall at San Francisco and to gain a better understanding of the part which these factors play in bringing about a rain-producing situation. The final stage of the study was the combination into a graphical procedure of the most effective factors in order to obtain an estimate of the rain-producing potentialities of a given synoptic situation. The availability of the necessary prognostic charts would lead to an objectively determined forecast based on the prognostic charts.

PROCEDURE

In order to investigate the factors responsible for rain at San Francisco, combinations of meteorological variables were studied by means of scatter diagrams on which were entered the occurrence or nonoccurrence of rain during a period centered at about the time of the meteorological observations. Data from the 1030 and 2230 PST sea level charts and 0700 and 1900 PST radiosonde and pilot balloon flights were used in connection with the rainfall occurring between 0430 and 1630 PST for the morning data and between 1630 and 0430 PST for the evening data. Thus, for this portion of the study, the sea level variables were taken at the midpoint of the 12-hour precipitation period and the upper air data about 3 hours after the beginning of the period. In as much as traces of precipitation may occur from either a rain situation or a fair weather fog or stratus condition, all traces were omitted from consideration in this portion of the study. In developing the quantitative aspects of the study, sea level data taken every 6 hours were correlated by means of a scatter diagram with the precipitation occurring during the 3 hours prior to and the 3 hours immediately following the observation. In this part of the study, traces were counted as no rain. The months of November through March of the 1950–51 and 1951–52 seasons were used in the development of the procedure and the 1948–49 and 1949–50 seasons were used as a test.

In analysing the scatter diagrams involving the meteorological variables, the smoothness and uniform spacing of the lines of equal probability were considered of primary importance. The general shapes and positions of the lines were determined by means of the methods of analysis presented by Brier [4] and Kangieser and Jorgensen [5]. The final positions were checked by determining the ratios of the rain to no-rain cases between the lines. However, if the attainment of the correct ratios was impossible without distorting the lines, the smoothness of the lines was allowed to take precedence over the correct ratio. This smoothing has the effect of assuming that large random variations may occur in the ratios in some portions of the chart due to the small amount of data used in determining these ratios. In analysing the scatter diagrams involving two probabilities, the formula given in [5] was used to describe the shapes of the lines (e. g., see fig. 5) with the positions of the lines adjusted to bring the channel frequencies more into harmony with the expected mean values. However, here again the smoothness of the lines and the symmetry of the configuration were not sacrificed. In general, the end charts were not believed to have sufficient data in the central portions to place the lines in this area with a high degree of accuracy. In analysing the quantitative charts (figs. 8 and 9), the general shapes of the lines were determined by inspection. Once the shapes of 2 or 3 random lines throughout the data were determined, lines of specific values were then located in such positions to give approximately the correct mean values of the plotted amounts in the areas between the lines. Here again, smoothness of the lines and uniform spacing were maintained at the expense of the channel means.

In order for the test of the procedure to be impartial and independent of the original development, the test was not carried out until the study was completed. Final probabilities and estimated amounts were obtained for all the test data and entered on the tabulation sheet before the actual amounts were entered.

CHOICE OF METEOROLOGICAL VARIABLES

Heavy rain in central California usually results from the occurrence off the coast of a cyclonic development in connection with associated occluded frontal systems, while lighter amounts of briefer duration are common as the result of frontal passages moving in from the west or northwest. In the case of heavy rains, the causative storm may vary greatly in size and mode of origin, with the movement into the area off the coast from almost any direction, but most generally from the southwest or west. The larger storm systems with their accompanying troughs may bring moist air into the area from tropical or subtropical latitudes and if persistent may lead to flood conditions. Storms moving into the coastal area from a northerly direction may have insufficient moisture to produce rain if the path is over land, but if over water, sufficient moisture may be accumulated in the storm to cause heavy rain. Cyclonic development along a frontal system approaching the coast may result in locally heavy rain, with heavy rain at San Francisco occurring when the center of the lowest pressure approaches the coast to the north of the station with the lowest pressure at Fort Bragg, Calif., or Eureka, or occasionally at San Francisco. Once the center of the Low has reached a position to the east or south of the station, rain usually ceases rather abruptly. Occasionally weak disturbances undergo rapid deepening as they approach the coast, the deepening apparently the result of conditions becoming favorable for storm development throughout the entire troposphere. Light rain of brief duration may occur under various other conditions.

A unique feature of the rainfall in California is the readily observable effect of the topography on the distribution and amount of rain from a given storm. The coastal mountain range and the Sierra Nevada act as permanent upglide surfaces. Thus, westerly rain-bearing winds are forced to rise with the resulting lifting becoming a predominant factor in the production of rainfall. As a consequence, the strength of the westerly flow over the area and the moisture content of the air become significant variables.

The search for meteorological variables was made on the assumption that vertical motion due to convergence and orographic lifting together with a sufficiently high moisture content of the air were adequate to account for the observed frequency and quantity of rainfall. Variables from the sea level and upper level charts were investigated. Widespread upward motions in the lower troposphere were assumed to be associated with the circulation about low pressure systems and widespread downward motions with the circulation about high pressure systems. Accordingly, the relationships between various sea level pressures and the corresponding weather were studied. Observation of the position of the jet stream during the winter season indicates that significant precipitation usually does not occur unless a zone of maximum westerlies at 500 mb. (lower portion of the higher jet stream) has migrated southward to a position near the station [6].

Regardless of the manner in which the rain situation develops, this study has shown that certain rather definite meteorological conditions need to be fulfilled in order for significant rain to occur. Among these conditions are: (1) Low pressure along the California coast at or to the north of San Francisco and relatively higher pressure to the south, a condition resulting from the presence of a storm offshore and leading to strong westerly flow over the coastal and interior mountains, (2) Sufficiently high moisture content of the air from the surface to about 10,000 feet, indicating that the previous history of the airmass was such as to allow the air to pick up a supply of moisture, and (3) Circulation in the upper air such as to give a zone of maximum westerly winds just to the north of the station with relatively low pressure-height values to the north and high values to the south.

PROCEDURE FOR ESTIMATING PROBABILITY OF RAIN OCCURRENCE

In order for the factors listed above to be taken into account in the estimation of rain occurrence, the following pairs of variables were incorporated into the estimating procedure:

(*a*) The sea level pressure difference, Santa Maria minus Fort Bragg, Calif., against the sea level pressure at San Francisco as shown in figure 1. The pressure difference furnishes evidence of the onshore flow, and the sea level pressure at San Francisco indicates the nearness or intensity of a low pressure system.

(*b*) The temperature-dew point difference at 700 mb. at Oakland against the same variable at 850 mb. These variables are plotted in figure 2. A small temperature-dew point difference indicates the nearness to saturation of the air or perhaps the actual existence of clouds. Once clouds have formed through a rather deep layer, a small amount of convergence or lifting will greatly increase the likelihood of rain.

(*c*) The height difference in the 500-mb. surface between Oakland and Medford against the difference between Santa Maria and Oakland as given in figure 3. Observation during several winter seasons indicates that a significant aspect of the upper air charts in determining the likelihood of rain at San Francisco is the position and strength of the zone of maximum winds above 10,000 feet. As shown in figure 3, a majority of rain cases occur with the height difference at 500 mb. between Oakland and Medford of 200 feet or greater with a somewhat lower value between Santa Maria and Oakland. This combination of variables brings into the estimating procedure the effect of the upper air flow.

(*d*) The height of the 500-mb. level at Medford against the sea level pressure at Eureka as shown plotted in figure 4. With the movement of storm centers onto the Washington and Oregon or extreme northern California coast, or the approach of fronts from the northwest, the sea level pressure at Eureka becomes a significant variable for the estimation of the occurrence of rain at San Francisco. A previous study [7] has shown that the significance of low pressure at Eureka is dependent on the circulation aloft. The lower pressures at Eureka are not so strongly indicative of rain at San Francisco when the 500-mb. height at Medford is relatively high. Thus, the combination of the 500-mb. height at Medford with the sea level pressure at Eureka increases the effectiveness of this latter variable.

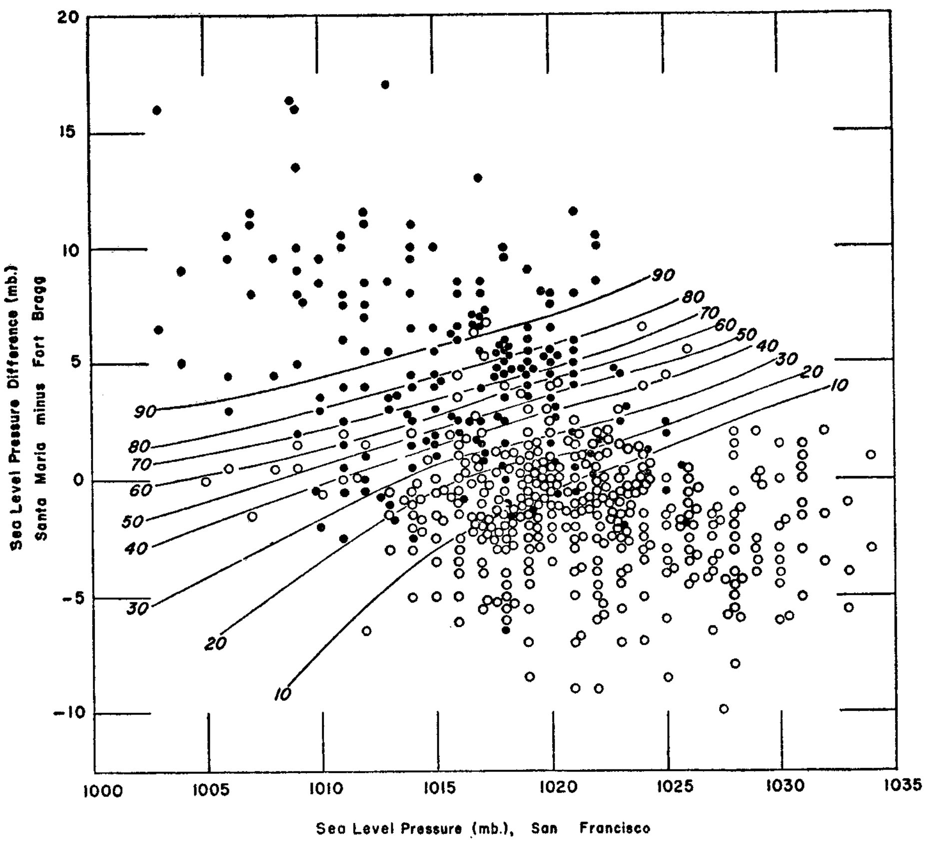

FIGURE 1.—Scatter diagram combining the sea level pressure at San Francisco and the difference in sea level pressure between Santa Maria and Fort Bragg, Calif. Circles represent no-rain cases and dots rain cases at San Francisco Airport with the observational period covering a 12-hour interval from 0430 to 1630 PST and from 1630 to 0430 PST. The pressure data are taken from the 1030 and 2230 PST sea level observations. Probability P_1 is read from this chart.

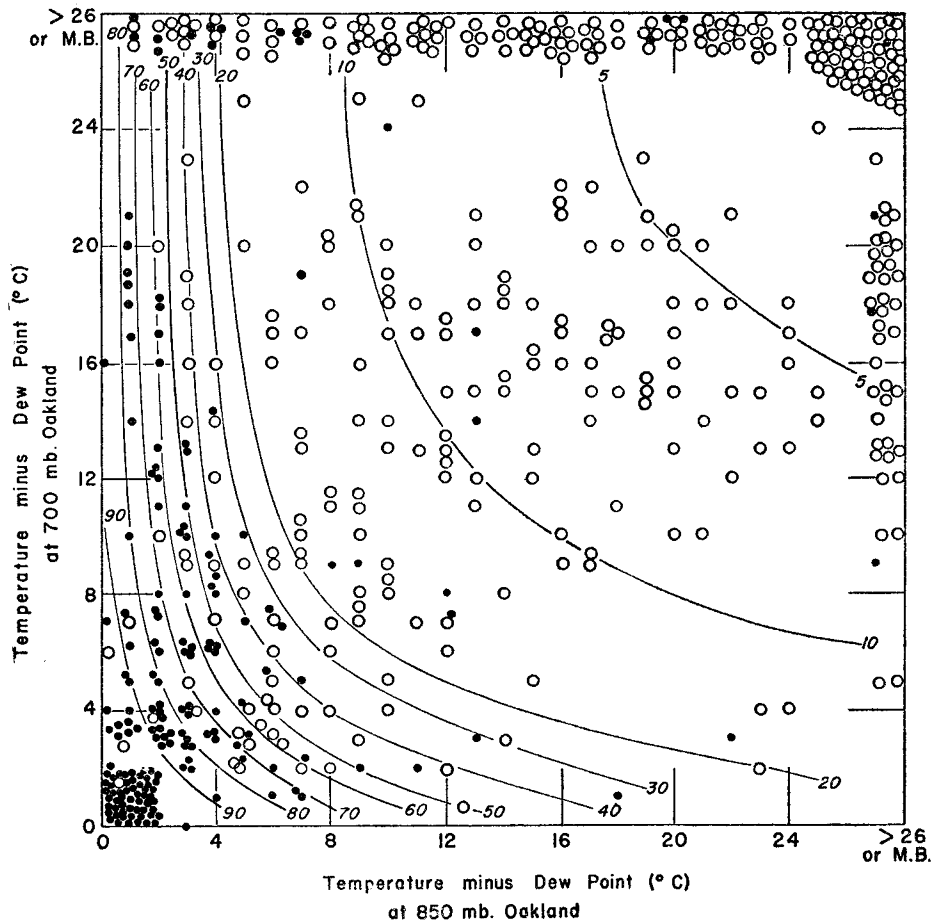

FIGURE 2.—Scatter diagram combining the temperature-dew point difference at the 850- and 700-mb. levels at Oakland in terms of the occurrence of rain or no-rain as in figure 1. The temperature and dew-point data are taken from the 0700 and 1900 PST radiosonde observations. Probability P_2 is read from this chart.

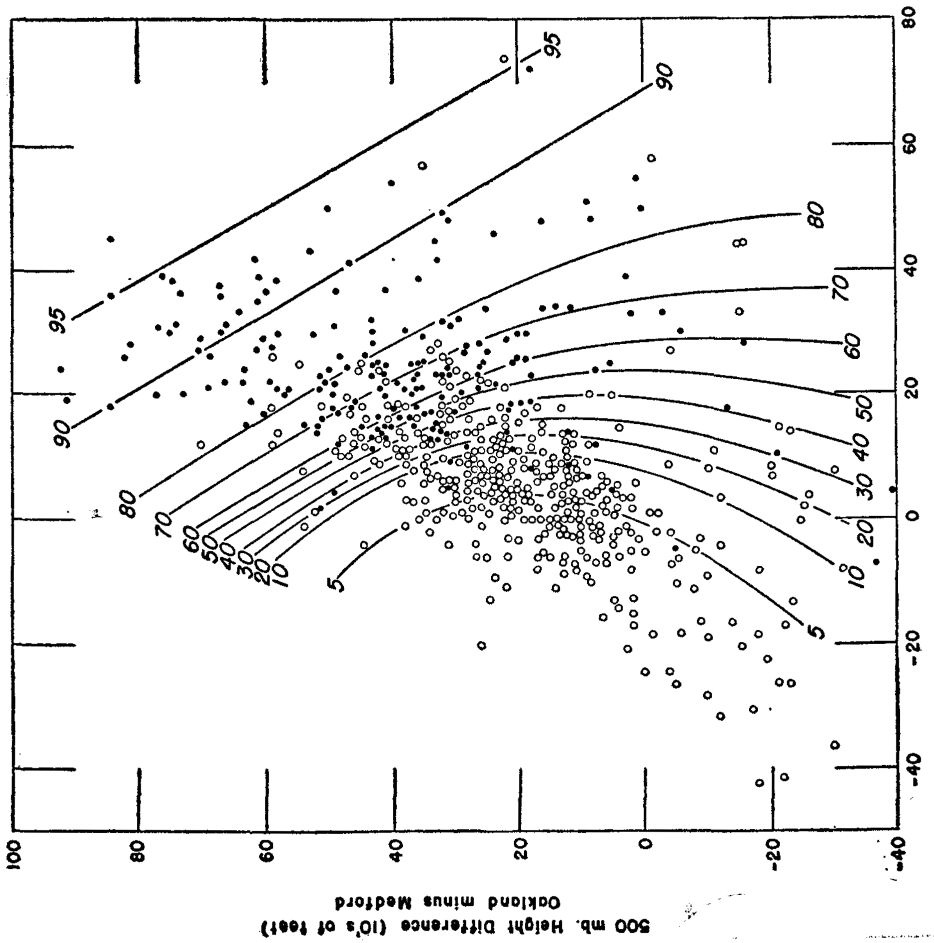

FIGURE 3.—Scatter diagram combining the height difference in the 500-mb. surface between Santa Maria and Oakland and between Oakland and Medford in terms of the occurrence of rain or no-rain as given in figure 1. The 500-mb. data are taken from the upper air observations as in figure 2. Probability P_3 is read from this chart.

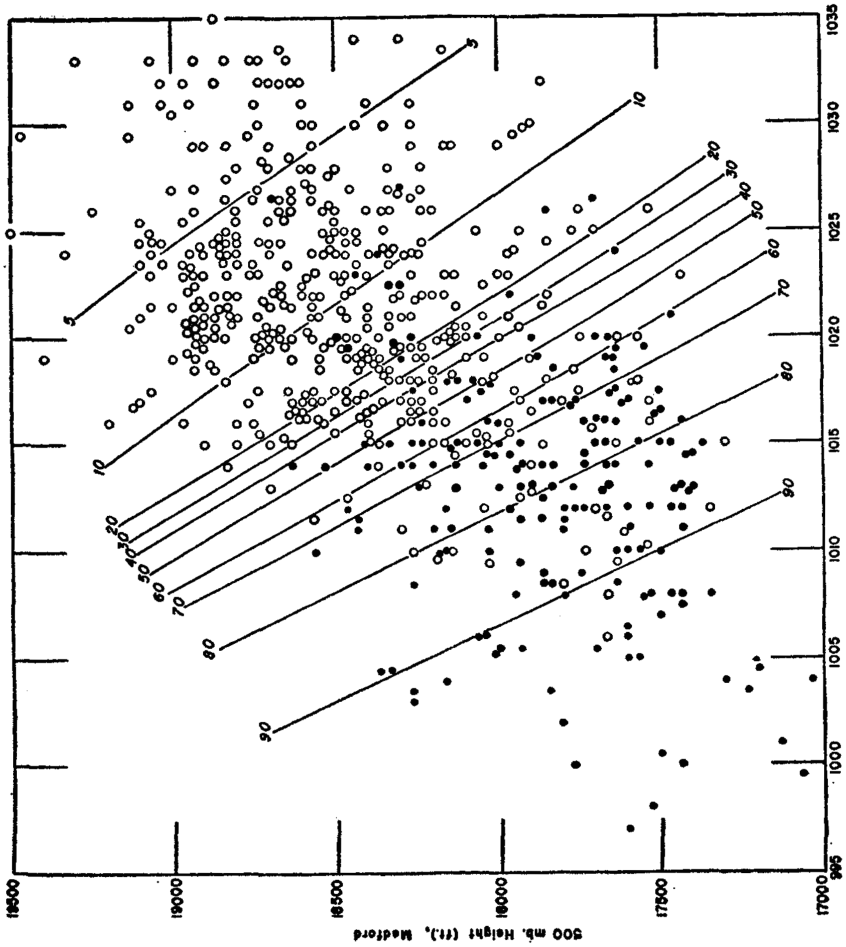

FIGURE 4.—Scatter diagram combining the sea level pressure at Eureka and the height of the 500-mb. level at Medford in terms of the occurrence of rain or no-rain as in figure 1. The data are taken from the observations as indicated in figures 1 and 2. Probability P_4 is read from this chart.

The four scatter diagrams thus developed have been combined according to the following outline:

Sea level pressure difference, Santa Maria minus Fort Bragg.	P_1 (fig. 1)	$P_{1,2}$ (fig. 5)	W (fig. 7)
Sea level pressure, San Francisco			
Temperature minus dew point at 700 mb., Oakland.	P_2 (fig. 2)		
Temperature minus dew point at 850 mb., Oakland.			
500-mb. height difference, Oakland minus Medford.	P_3 (fig. 3)	$P_{3,4}$ (fig. 6)	
500-mb. height difference, Santa Maria minus Oakland.			
500-mb. height, Medford	P_4 (fig. 4)		
Sea level pressure, Eureka			

In the scatter diagrams the combined variables are evaluated in terms of the probabilities, P, which in turn are combined into the final parameter, W, expressing the overall probability for rain to occur as a result of the existing variables.

The estimate of the probability of rain occurrence may vary over the full range of values from near zero to close to 100 percent. For the purpose of expressing the accuracy of the various charts the percentage of correct estimates based on the 50 percent line is used. Counting as errors the no-rain cases falling above the 50 percent line and the rain cases falling below the line, percentages are obtained representing the accuracy of the charts. For the initial charts, the percentage correct ranges from 86.5 to 88.3 for the dependent data and 79.6 to 90.6 for the test data. The final chart gives a percentage correct of 92.9 and 92.8 for the respective groups of data. In general, the higher the probability of occurrence the greater is the expected amount. Rainfall amounts are usually light when they occur with an expectancy below 50 percent.

An inspection of the scatter diagrams leading to the final parameter W shows a gradual accumulation of the

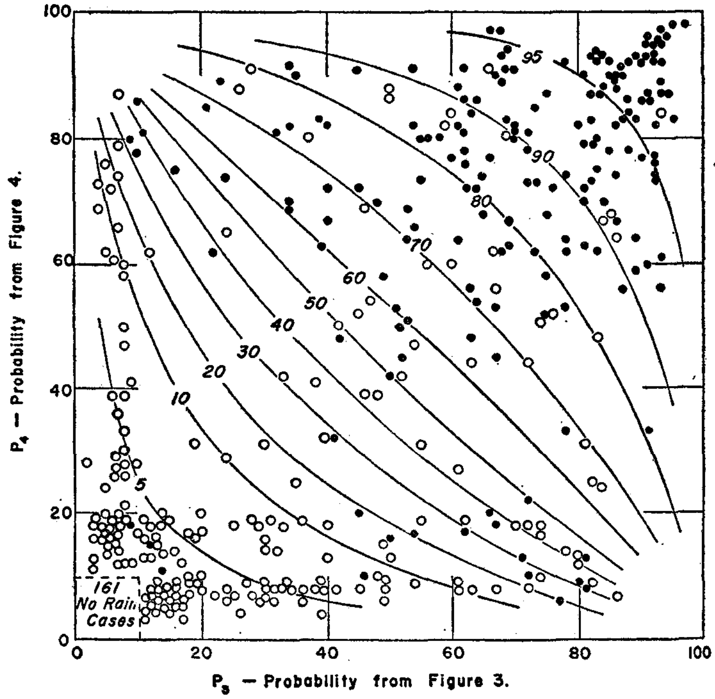

FIGURE 6.—Scatter diagram combining the probabilities obtained from figures 3 and 4 and giving the probability $P_{3,4}$.

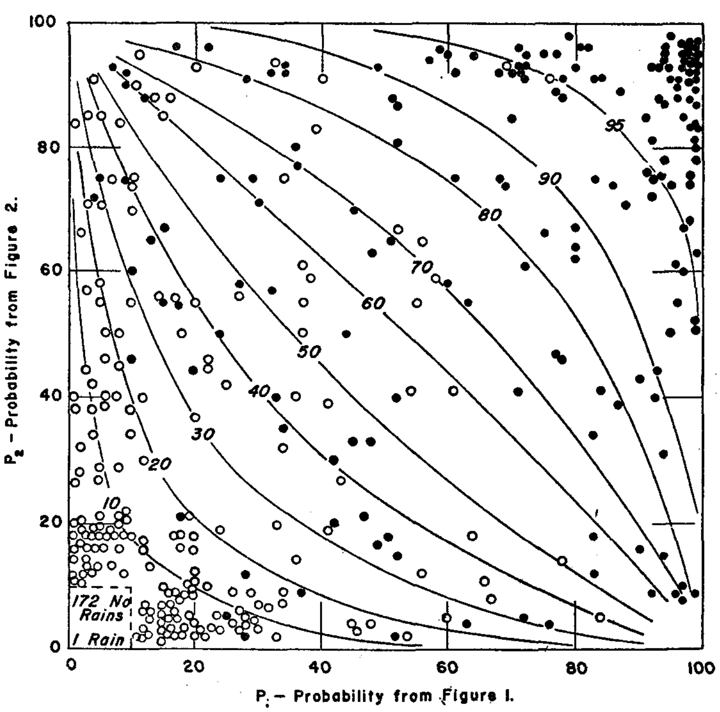

FIGURE 5.—Scatter diagram combining the probabilities obtained from figures 1 and 2 and giving the probability $P_{1,2}$.

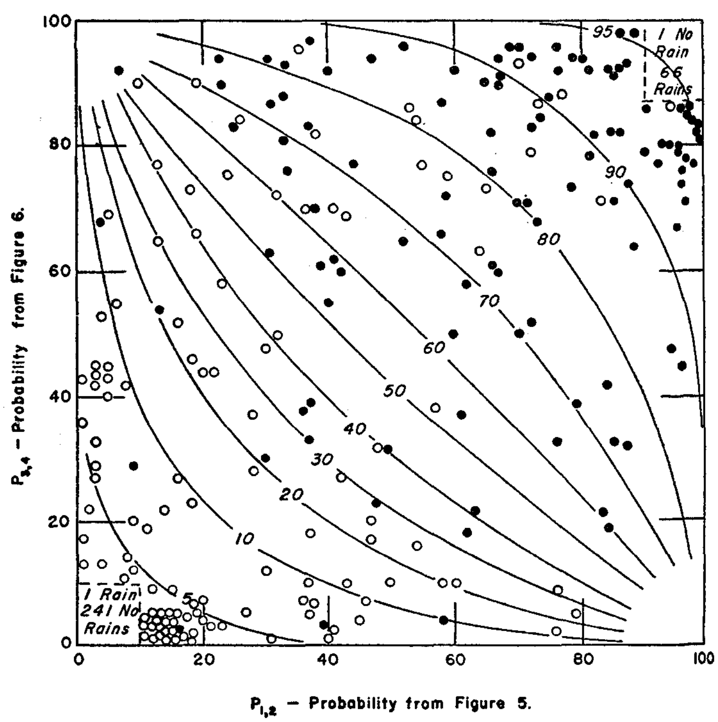

FIGURE 7.—Scatter diagram combining the probabilities obtained from figures 5 and 6 and giving the final probability W.

rain cases in the high probability areas of the charts and the no-rain cases in the low probability areas. This shifting of the cases to the upper right- and lower left-hand corners suggests that in the perfect final chart all the rain cases would fall at 100 percent probability and all the no-rain cases at zero percent probability. (At this point there would be no useful relationship between the probability of occurrence and the expected amount.) The degree to which the contrasting weather types are shifted to opposite corners of the charts becomes a measure of the confidence which may be placed in the use of the chart. For example, in figure 1, 40.2 percent of the rain cases fall above the 90 percent line compared to 59.2 percent which fall above the same line on the final chart in figure 7, the gain of 19 percent resulting from the additional sets of variables. Similarly, 68.6 percent of the no-rain cases fall below the 10 percent line in figure 1 compared to 84.9 percent which fall below the same line in the final chart. Listed in table 1 for the charts in figures 1 through 7 are the percentage of correct cases based on the 50 percent line, the percentage of rain cases above the 90 percent line, and no-rain cases below the 10 percent line for both the dependent and test data. As may be seen, there is a gradual improvement in both features up to the final chart.

TABLE 1.—*Tabulation of the percentage of estimates correct based on the 50 percent line, the percentage of rain cases above the 90 percent line, and the no-rain cases below the 10 percent line. (Data based on 12-hourly periods.)*

A. Dependent data (537 cases)

	Scatter diagram						
	P_1	P_2	P_3	P_4	$P_{1,2}$	$P_{3,4}$	W
Percentage correct	88.3	86.6	86.3	88.1	91.8	90.0	92.9
Percentage of rain cases above 90% line	40.2	34.5	17.7	21.5	50.6	51.9	59.2
Percentage of no-rain cases below 10% line	68.6	64.1	59.2	61.6	75.3	79.4	84.9

B. Test data (501 cases)

	Scatter diagram						
	P_1	P_2	P_3	P_4	$P_{1,2}$	$P_{3,4}$	W
Percentage correct	87.6	90.6	79.6	85.4	92.0	86.6	92.8
Percentage of rain cases above 90% line	27.7	42.4	18.2	13.6	47.0	44.7	56.1
Percentage of no-rain cases below 10% line	79.3	65 3	53.6	61.5	85.4	73.6	86.7

The skill score, based on the 50 percent line for the final chart, W, for the dependent data is 0.843 and for the test data 0.812. The score is obtained from the expression

$$\text{Skill score} = \frac{C - E_c}{T - E_c}$$

in which T = number of estimates made

C = number of estimates correct

E_c = number of estimates expected to be correct with the estimates distributed at random over the period covered by the data.

PROCEDURE FOR ESTIMATING PRECIPITATION AMOUNTS

With the probability of rain occurrence rising to above 50 percent (the usually assumed value), it is then necessary to estimate the amount of rain to be expected from the given synoptic situation. Although there is a significant correlation between the probability of occurrence and the expected amount, the relationship has decreased significance at the higher values of the probabilities. This decreased significance results from the fact that once the situation is favorable for "heavy" rain, the probability of occurrence remains nearly the same even though the heavy rain may vary considerably in amount. In addition, it is found that the value of W may vary greatly during a 12-hour period, the change sometimes amounting to as much as 90 percent between two successive periods. Under these changeable conditions observations every 12 hours are too infrequent to be satisfactory for use in the estimation of rainfall amounts. Variables which lend themselves to more frequent evaluations are desirable.

In evaluating the primary charts in terms of the estimation of rainfall amounts, the combination of variables involving the sea level pressure difference between Santa Maria and Fort Bragg and the sea level pressure at San Francisco were found to give the best quantitative results. Since these variables may be evaluated every 6 hours, they have been used in this part of the investigation. A study of the amounts expected reveals that when closed circulation prevails at 10,000 feet in the vicinity of the station, the surface variables chosen have somewhat different significance from a quantitative standpoint. For this reason, the situations have been divided into two types depending upon whether or not a closed Low is present at 700 mb. within the area bounded by the 115° and 130° W. meridians and the 25° and 45° N. circles of latitude. Those situations not involving a closed Low and making up a large majority of the cases are shown in figure 8, while the 10 to 15 percent of the situations during which a closed Low existed in the designated area are given in figure 9.

In developing the charts given in figures 8 and 9, the sea level pressure data taken at the 6-hourly map times have been used, with the rainfall amount occurring within the 3 hours before and the 3 hours after the observation plotted on the charts. Only those 6-hourly data are plotted for which the value of W is 50 percent or higher. The value of W obtained from the 1000 PST sea level and 0700 PST upper air data is assigned to the 1000 PST and 1600 PST observations, and similarly, the W obtained from the 2200 PST sea level and 1900 PST upper air data is assigned to the 2200 PST and the following 0400 PST observations. In this part of the study, when missing data prevented the full evaluation of W, the data available were used to give an estimate of the value of the parameter. Estimated 6-hourly amounts have been obtained for the test period, November through March 1948–49 and 1949–

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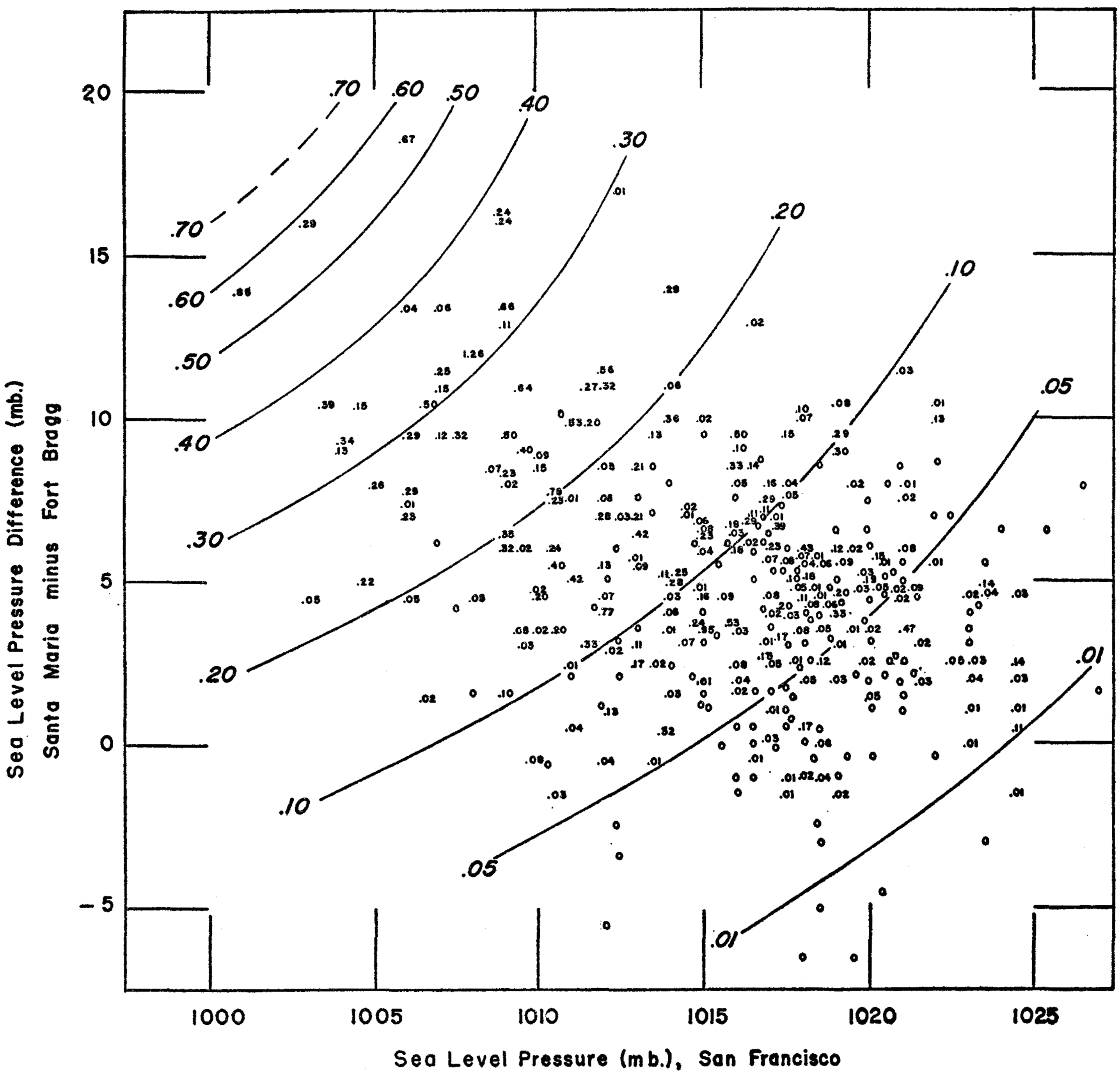

FIGURE 8.—Scatter diagram used for the estimation of 6-hourly precipitation amounts for those cases for which *W* is greater than 50 percent and no closed Low exists at 700 mb. in the designated area. (For designated area see text.) The data are taken from the 6-hourly observations with the rain period covering the interval within plus or minus three hours of the time of observation.

50. These amounts have been combined into 24-hour totals (24 hours beginning at 0100 PST) and are compared with the observed amounts in table 2.

CONCLUSION

For the particular station under consideration, the precipitation to be expected from a given synoptic situation may be estimated with worthwhile accuracy by means of sea level pressures, 500-mb. heights, plus a variable indicating the moisture content of the air. It is concluded that the procedure thus developed may be used as an objective aid in the interpretation of prognostic charts in terms of the expected weather. The substituiton of predicted values of the variables in place of the current values

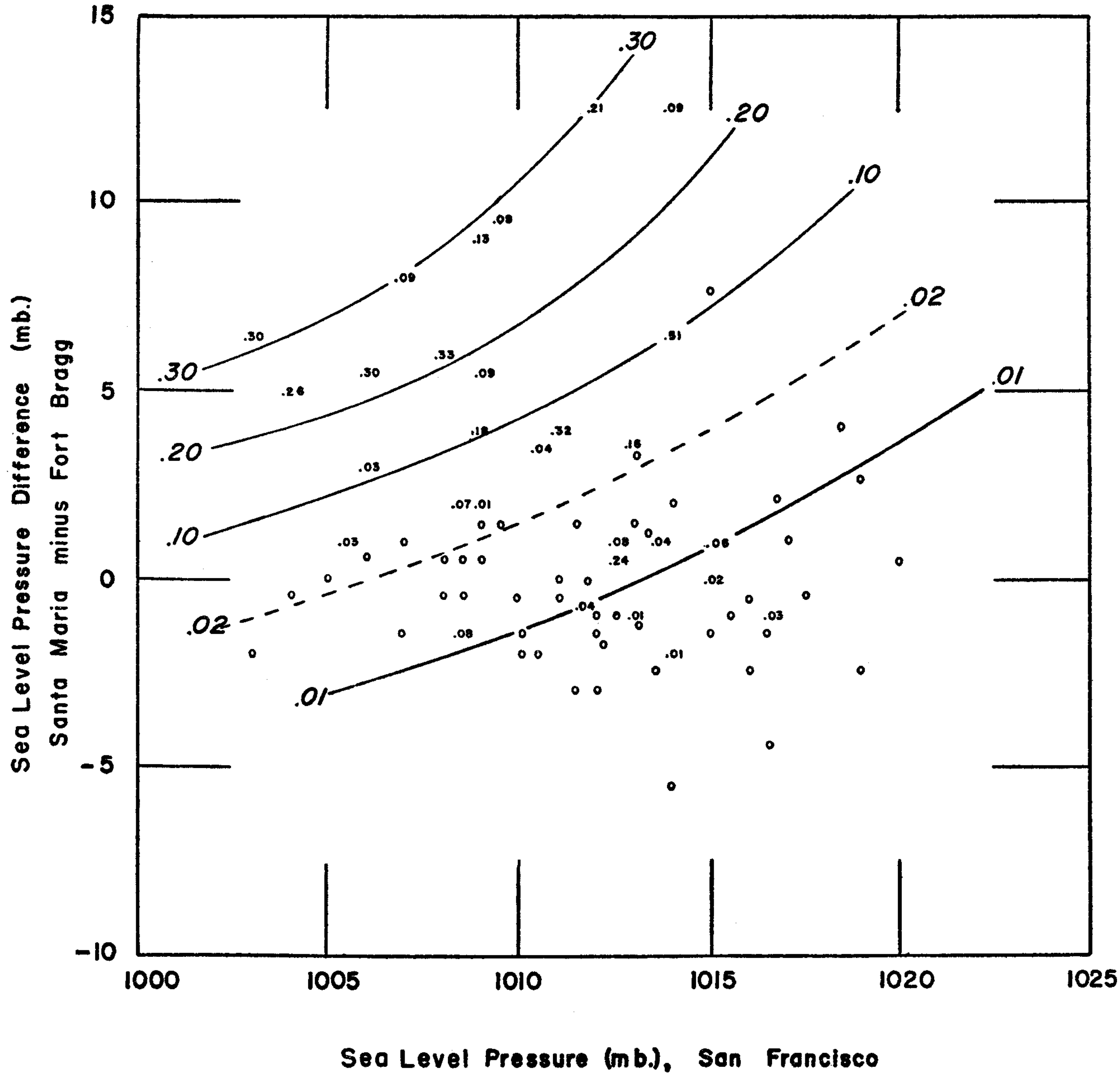

FIGURE 9.—Scatter diagram similar to that given in figure 8 except that a closed Low exists in the designated area.

will indicate the weather expected to accompany the prognosticated conditions. The success of this type of forecasting procedure lies in the accuracy with which the necessary variables may be predicted. The use of such a system for a trial period will determine its effectiveness.

Considerable variation is noted in the day-to-day agreement between the estimated and observed amounts given in table 2. This variation is unfavorable for the use of the procedure in evaluating the effects of weather modification efforts. However, the monthly and seasonal totals are sufficiently in agreement to promise some usefulness when the weather modification attempts are extended over a prolonged period.

ACKNOWLEDGMENTS

Appreciation is expressed to Mary E. Stoneback for her aid in the tabulation of the data and in drafting the final charts.

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TABLE 2.—*Tabulation of estimated and observed amounts of rainfall for the test period*

Date	November				December				January				February				March			
	1948		1949		1948		1949		1949		1950		1949		1950		1949		1950	
	Est.	Obs.	Est.	Obs.	Est.	Obs.	Est.	Obs.	Est.	Obs.	Est.	Obs.	Est.	Obs.	Est.	Obs.	Est.	Obs.	Est.	Obs.
1	0.20	0.03							0.09	0.12	0.03						0.37	0.13		
2	.14	.04			0.11	0.10					.06	0.15	0.13	0.27			.89	.62		
3	.05	.11			.10	.22							.20		0.39	0.72	.36	.17		
4					.01		0.04	0.11			.06		.28	.60	.61	.81	.06	.09		
5					.23	.21	.01	.07							.61	.66	.03	.09	0.05	0.05
6							.10						.30	.48	.14			.03		
7			0.09	0.20	.03	.05	.40	.88			.56	.34	.07	.02			.02	.01		
8			.41	.01							.51	.50					.01	.03		
9			1.31	1.29							.24	.05			.12	.16	.91	.43	.06	
10			.38	.01							.62	1.23	.14	.18	.24	.26	1.18	.62	.01	
11											.24	.24	.29	.31			.84	.70	.02	.01
12					.20	.09					.04	.19	.05							
13					.51	.23			.29		.42	.73					.12			
14					.32	.18	.02	.26			.17	.23					.14			.01
15		.01			.08			.11			.03						.56	.12		
16	.07				.60	.54	.12	.02			.52	1.04					.32	.01		
17					.06	.04	.54	.30			.21	.50					.08		.01	.04
18							.40	.61	.05	.05	.10						.31	.12	.06	.01
19	.04	.06					.04		.39	.67							.18	.67	.06	.10
20									.03		.02		.17	.02						
21									.28	.13	.02	.06	.02						.04	.02
22									.20	.27			.04	.01			.40	.41	.05	.14
23											.12	.03	.13	.17			.05	.03	.30	.86
24					.41						.10	.04	.18	.45					.47	.38
25	.02	.02			.24	.73													.15	.01
26					.28	1.44							.03	.09					.12	
27					.06	.22					.35	.83							.01	
28											.06	.11	.02	.01						
29							.02													
30							.01					.01								
31						.02														
Totals	.52	.27	2.19	1.51	3.24	4.07	1.70	2.36	1.33	1.24	4.48	6.28	2.05	2.64	2.11	2.61	6.83	4.28	1.41	1.63

Est.	1948–49	13.97	1949–50	11.89	Total	25.86
Obs.	1948–49	12.50	1949–50	14.39	Total	26.89

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